Outlook for Underfloor Air Distribution

By Fred Bauman, P.E., and Tom Webster, P.E.
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Underfloor air distribution (UFAD) is an innovative technology that uses the underfloor plenum below a raised floor system to deliver space conditioning in offices and other commercial buildings. The use of UFAD is increasing in North America because of the benefits that it offers over conventional ceiling-based air distribution.

Well-designed UFAD systems can:

• Reduce life-cycle building costs by improving flexibility in reconfiguring building services in response to churn;

• Improve thermal comfort, occupant satisfaction, and productivity by providing individual comfort control;

• Improve ventilation efficiency, indoor air quality, and health by delivering fresh air in the vicinity of building occupants;

• Reduce energy use from thermal stratification, reduced static pressures, and increased economizer operation;

• Reduce floor-to-floor height in new construction by lowering the height of service plenums and/or by changing from standard steel beam construction to a concrete (flat slab) structural approach.[1]

Considered a fringe practice in new office construction as recently as 1995, some designers and manufacturers predict that 35% of new offices will use raised floors and half of those installations will use UFAD by 2004. The installed market value of raised flooring in the U.S., which was estimated to be $200 million in 2000, is projected to rise to at least $1 billion by 2004.[2]

UFAD systems are being designed and installed although a standardized set of design tools and guidelines supported by fundamental research has not been developed. This trend is likely to continue until crucial research has been completed and the industry has gained the knowledge and experience to consistently apply UFAD systems. This article provides a current assessment of UFAD technology by describing key features of system design and operation, potential advantages over conventional practice, limitations and needs of the technology, and ongoing work to advance UFAD technology.

System Description

UFAD systems are similar to conventional overhead systems in terms of the types of equipment used at the cooling and heating plants and primary air-handling units (AHU). Key differences include use of an underfloor air supply plenum, warmer supply air temperatures, localized air distribution (with or without individual control) and the resulting floor-to-ceiling airflow pattern, and the solutions used for perimeter systems.

When configuring a UFAD system, there are three basic approaches: 1) pressurized plenum with a central air handler delivering air through the plenum and into the space through passive grilles/diffusers, modulated diffusers, and fan-powered mixing boxes; either used alone or in combination with one another; 2) zero-pressure plenum with air delivered into the conditioned space through local fan-powered (active) supply outlets in combination with the central air handler; and 3) in some cases, ducted air supply through the plenum to terminal devices and supply outlets.

Approach 1 appears to be the focus of current practice, although zero-pressure plenums pose no risk of uncontrolled air leakage to the conditioned space or adjacent zones. Many perimeter zone solutions have been applied successfully. Fan-powered supply units often are used to increase the rate at which the system can respond to changes in load. For all systems, energy-efficient envelope design is the first stage of defense against excessive perimeter loads.

Historically, the approach to HVAC design in commercial buildings has been to supply conditioned air through extensive duct networks to an array of diffusers spaced evenly in the ceiling. Conditioned air is supplied and returned at ceiling level. Ceiling plenums are deep to accommodate the large supply ducts. Return air is most commonly configured as a nonducted ceiling plenum return.

Often referred to as mixing-type air distribution, conventional HVAC systems are designed to promote complete mixing of supply air with room air, thereby maintaining the entire volume of air in the occupied space at the desired setpoint temperature and evenly distributing ventilation air. This control strategy provides little opportunity (other than by increasing the number of zones) to accommodate different thermal preferences among the occupants or to provide preferential ventilation in the occupied zone. In open plan offices, even by adding more zones, overhead systems can never allow individual control of local workstation environments.

Underfloor systems are integrated sys-

About the Authors

Fred Bauman, P.E., and **Tom Webster, P.E.,** are research specialists for the Center for the Built Environment, University of California, Berkeley, Calif.

tems that share the open space (underfloor plenum) between the structural concrete slab and the underside of a raised floor system with power and communications wiring to deliver conditioned air directly into the occupied zone of the building (*Figure 1*). Supply outlet temperatures are maintained at or above 63°F–64°F (17°C–18°C) to avoid uncomfortably cool conditions for the nearby occupants.

Underfloor systems are generally configured to have a large number of smaller supply outlets, many close to the building occupants, as opposed to the larger diffusers and spacing used in conventional overhead systems. Outlets may be floor diffusers, or, particularly when part of a task/ambient conditioning (TAC) system, desktop or partition outlets equipped with individual control. Outlets are typically adjustable, providing an opportunity for nearby occupants to have some amount of control over local thermal comfort conditions. Air is returned from the room at ceiling level, or at the maximum allowable height above the occupied zone. This produces an overall floor-to-ceiling airflow pattern that takes advantage of the natural buoyancy produced by heat sources in the office and efficiently removes heat loads and contaminants from the space, particularly for cooling applications.

During cooling conditions (required year-round in many interior office spaces), underfloor system operation can be optimized to promote some amount of stratification in the space, with elevated temperatures and higher levels of pollutants above head height where its effect on occupants is reduced.[3]

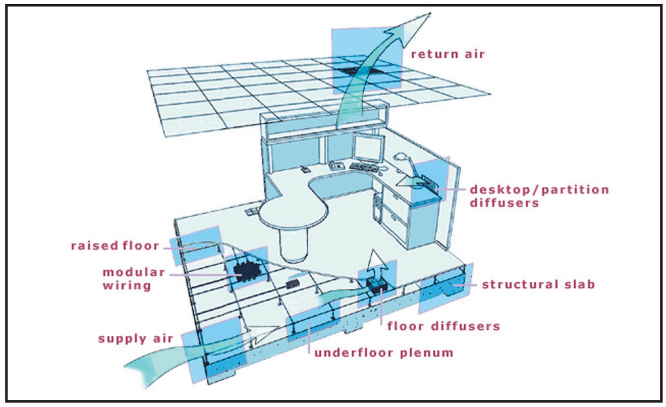

Figure 1: Cutaway of typical office work space with underfloor air distribution.

Figure 2: Open plan office with one floor diffuser per workstation.

Benefits

Well-engineered UFAD systems can provide:

1. Reduced life cycle building costs. In modern businesses, churn is a fact of life. A 1997 survey found the national average churn rate (defined as the percentage of workers per year and their associated work spaces in a building that are reconfigured or undergo significant changes) to be 44%.[4] The cost savings associated with reconfiguring building services is a major factor in the decision to install access flooring. By integrating a building's HVAC and cable management systems into one easily accessible underfloor plenum, floor diffusers along with power, voice, and data outlets can be placed almost anywhere on the raised floor grid. In-house maintenance personnel can carry out these reconfigurations at significantly reduced expense using simple tools and modular hardware.

Disregarding architectural and office furniture cost differences and assuming the 44% national average churn rate, the savings between conventional overhead and UFAD systems in reconfiguring the HVAC and electrical distribution has been estimated at \$1.50 to \$2.30/ft^2 (\$16 to \$25/m^2).[5,6] Firms that are more likely to install underfloor systems are also more likely to churn at a higher rate. Companies are finding that any additional first costs of the underfloor system can be paid back with the first churn.

2. Improved thermal comfort. By allowing occupants to control their local thermal environment, their individual comfort preferences can be accommodated. In today's work environment, significant variations exist in individual comfort preferences due to differences in clothing, activity level (metabolic rate), and individual preferences. As an example of the variations, a person walking continuously around in an office (1.7 met [99 W/m^2]) will experience an effective temperature of the environment that is approximately 3°F–5°F (2°C–3°C) warmer than a person sitting quietly at their desk (1.0 met [58 W/m^2]), depending on clothing level.

Recent laboratory tests show that commercially available task/ambient conditioning systems with fan-driven supply outlets (airflow directed at the occupant) provide personal control of an occupant's microclimate over a sizable range: up to 13°F (7°C) for desktop outlets and up to 9°F (5°C) for floor-based outlets.[7] This amount of control is more than enough to accomodate the full range of individual thermal preferences.

Passive diffusers (diffusers that do not rely on local fans), such as swirl floor diffusers, will not provide the same magnitude of control, but can still be effective even if they provide a 3°F–5°F (2°–3°C) temperature range (see *Figure 2* for an example open plan office with one floor diffuser assigned to each workstation). In addition, recent field research has found that building occupants who have no individual control capabilities are twice as sensitive to changes in temperature compared to occupants who do have individual thermal control.[8]

3. Improved ventilation efficiency and indoor air quality. Some improvement in ventilation and indoor air quality at the breathing level can be expected by delivering the fresh supply air at floor level and returning at the ceiling, resulting in an upward displacement of indoor air and pollutant flow pattern. This is similar to the flow pattern achieved in displacement ventilation systems commonly used in Scandinavia. Displacement ventilation systems (used for cooling only) typically achieve their improved ventilation performance by supplying 100% outside air at a temperature slightly below comfort conditions and at a very low velocity (<100 fpm [0.5 m/s]). Because the supply air has little momentum, buoyancy forces influence the airflow pattern and the supply air spreads out at floor level and then flows upward. Air temperatures and concentrations of some pollutants increase with height in the displacement zone. Depending on the balance of heat sources and overall supply volume into the room, displacement systems will produce a lower region with an upward displacement (i.e., stratified) airflow pattern and an upper region that is reasonably well mixed.

Because UFAD systems supply air at higher outlet velocities than true displacement systems, greater mixing will occur, diminishing the degree of displacement flow. In addition, the recirculation of indoor air by some underfloor systems will cause mixing of indoor air and pollutants. An optimized strategy is to design the floor diffuser system to allow mixing of supply air with room air only in the occupied zone (up to 4–6 ft [1.2– 1.8 m]). Above this height, stratified and more polluted air is allowed to occur. The air that the occupant breathes will have a lower percentage of exhaust compared to conventional uniformly mixed systems.

Laboratory studies of floor supply systems have shown that ventilation performance can be improved under full economizer mode (100% outside air) and lower air supply volumes that reduce mixing — a 20–40% reduction in age of air in the breathing zone was shown.[3] Another benefit of providing local air supply is that it increases air motion in the space and prevents the sensation of stagnant air conditions, often associated with poor air quality.

4. Reduced energy use. Energy savings over conventional overhead systems are predominately associated with two factors: cooling energy savings from economizer operation and increased chiller COP and, fan energy savings. Economizer savings result from 1) increased hours of economizer operation due to higher return air temperatures caused by stratification (77–86°F [25–30°C] vs. 75°F [24°C] for overhead systems) and 2) the delay in chiller activation and reduction in cooling energy use due to higher supply air temperatures (63–68°F [17–20°C] vs. 55°F [13°C] for overhead systems). If air volumes for the UFAD system are reduced, then the magnitude of the economizer savings lessens, but the total cooling energy is still significantly reduced.

Chiller savings result from using higher chiller leaving water temperatures due to the higher supply air temperatures. However, these cooling energy savings can be substantially reduced or eliminated under either of two scenarios: moisture control in humid climates will require the use of conventional coil leaving air temperatures, and in a hybrid system configuration, operation of a conventional air-distribution system cooled by the same AHU (e.g., serving a data center) could also require conventional coil leaving temperatures.

Fan energy savings are associated with reduced static pressure requirements and the potential for reduced air volumes. The stratified floor-to-ceiling airflow pattern in UFAD systems allows most convective heat gains from sources outside the occupied zone to be returned directly at ceiling level, and therefore to not be included in the airside load. The determination of air supply volumes required to maintain a given comfort condition are based on the combination of the following factors: behavior of thermal plumes generated by heat sources in the occupied zone and at the windows, floor-diffuser operating characteristics, cooling provided by heat transfer through the floor panels, and system design and control. Depending on how these factors interact, overall supply air volume can range from significantly below to somewhat above that of conventional mixing systems despite the warmer supply air temperatures.

Static pressures are reduced for most UFAD designs due to the elimination of most branch ductwork as the supply air flows freely through the underfloor plenum at low plenum pressures (typical pressures are 0.1 in. H_2O (25 Pa) or less). From a recent analysis of supply fan energy use in UFAD systems, the average savings using a variable air volume (VAV) control strategy over conventional VAV systems was estimated to be about 48%.[9] Characterization of additional potential energy savings due to, for instance, using the mass of the concrete floor for thermal energy storage with night ventilation, is being addressed by ongoing research.

5. Reduced floor-to-floor height in new construction. Buildings using UFAD have the potential for a 5–10% reduction in floor-to-floor heights compared to projects with conventionally designed ceiling-based air distribution. This can be accomplished by reducing the overall height of service plenums and/or by changing from standard steel beam construction to a concrete (flat slab) structural approach. A single large overhead plenum to accommodate large supply ducts can be replaced with a smaller ceiling plenum for air return combined with a lower height underfloor plenum for unducted airflow and other building services.[10] Floor-to-floor heights for overhead systems using steel beam construction also can be reduced by using beam penetrations for ducts and other building services. Concrete flat slab construction can take longer than steel beam construction, but is preferred for underfloor systems due to thermal storage benefits, and reduced vertical height requirements.

6. Improved productivity and health. Research evidence indicates that occupant satisfaction and productivity can be increased by giving individuals greater control over their local environment and by improving the quality of indoor environments (thermal, acoustical, ventilation, and lighting). A recent analysis of previous research indicates that individual control of local cooling and heating equivalent to ±5°F (3°C) can improve group work performance by 3% to 7%, depending on the nature of the task.[11] Another review of relevant research has concluded that improvements in productivity of 0.5% to 5% may be possible when the thermal and lighting indoor environmental quality is enhanced.[12] These percentages have a life-cycle value approximating that of capital and operating costs of an entire building! Improved ventilation and thermal environments, which UFAD systems can provide, have also been associated with a reduction in the prevalence or severity of adverse indoor health effects.[12]

Technology Needs

Despite the advantages of underfloor systems, barriers exist to widespread adoption of UFAD technology. There is a perceived higher risk to designers and building owners due to a lack of objective information and standardized design guidelines, perceived higher costs, limited applicability to retrofit construction, problems with standards and codes, and a lack of documented case studies with whole-building performance and cost-savings data. These barriers are summarized below along with how these technology needs are being addressed.

1. New and unfamiliar technology. For the majority of building owners, developers, facility managers, architects, engineers, and equipment manufacturers, UFAD systems still represent a relatively new and unfamiliar technology. Lack of familiarity can create problems throughout the entire building-design, construction, and operation process including higher cost estimates, incompatible construction methods, and incorrect building control and operation on the part of facility managers and building occupants. As UFAD technology continues to grow, these problems should become less prevalent.

2. Lack of information and design guidelines. Although in recent years there have been an increased number of publications on UFAD technology, including some with design methods, a set of standardized design guidelines still does not exist. Designers having experience with UFAD systems have developed guidelines of their own. ASHRAE is funding a research project (1064-RP) to develop a design guide on task/ambient conditioning and UFAD systems, making it available to the professional design and engineering community at large. A web site on UFAD technology has also been developed by the authors (www.cbe.berkeley.edu/underfloorair).

3. Gaps in fundamental understanding. There is a need to improve the fundamental understanding of several key issues related to energy and comfort performance of UFAD system design. These issues include:

a. Room air stratification. What fraction of the convective heat sources in the space will rise up as thermal plumes and be exhausted directly at ceiling level and can therefore be neglected in the calculation of the room cooling load? Although some empirical design methods exist,[13] an understanding of controlled/optimized thermal stratification is critical to provide designers with a reliable energy-estimating tool as well as a sound basis to develop design tools and guidelines.

b. Underfloor air supply plenum. An important difference between conventional and UFAD system design is the heat exchange between the concrete slab, raised floor panels, and the supply air as it flows through the underfloor plenum (*Figure 3*). If the slab has absorbed heat, particularly from warm return air flowing along the underside of the slab from the next floor down, then supply temperature will increase with distance from the primary air inlet to the plenum. Energy and operating cost savings can be achieved by using the concrete slab in a thermal storage strategy, but further research is still needed to optimize and quantify this effect.

c. Whole-building performance. There does not exist a whole-building energy simulation program capable of accurately modeling UFAD systems. This is one of the top technology needs identified by system designers. Also, whole-building performance data are needed from completed UFAD projects in the form of energy use, indoor environmental quality, occupant satisfaction, comfort, health, performance, and first and life-cycle (operating) costs to quantify the relative benefits of the technology.

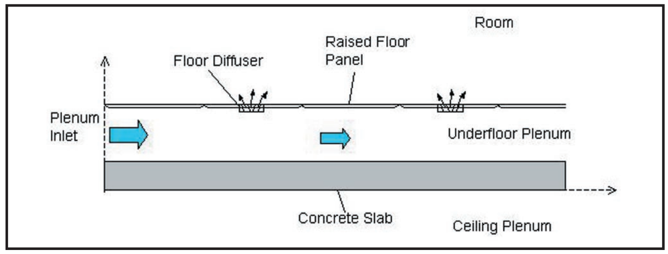

Figure 3: Underfloor plenum schematic.

The authors, other research institutions, equipment vendors, and design firms are currently conducting research to address these issues, as well as other areas of UFAD technology.

4. Perceived higher costs. The perceived higher cost is one of the main reasons why UFAD technology has been slowly adopted by the U.S. building industry. As discussed earlier, this situation is now changing due to significant savings in life-cycle costs. Typically the added first cost of the access floor will be somewhat higher than the cost reductions associated with decreased ductwork and cable and wire installation (~$3/ft^2 [$32/m^2]). However, frequently these projects are “sold” on the basis that UFAD is an add-on after the choice has been made to install access flooring for its cable management and reconfiguration benefits for high churn businesses. Considered in this light, the first cost of a UFAD system actually can be less than a conventional system. This technology is still in its early stages of adoption and will see cost reductions as volumes increase and more UFAD specific products become available.

5. Limited applicability to retrofit construction. The installation of UFAD systems and the advantages that they offer are most easily achieved in new construction. However, the widespread use of underfloor air distribution in renovation work has been restricted by the feasibility of adding a raised floor in the majority of buildings having limited floor-to-floor heights, and due to the high cost of adjusting stair and elevator landings and toilet room floors to the raised floor level. In retrofits with high-bay spaces, UFAD can reduce complexities involved in providing overhead distribution and can contribute to creating an expansive, uncluttered interior, improving the visual and spatial character of the workplace.

Current practice calls for typical raised floor heights of 12–18 in. (0.30–0.46 m). A recent full-scale field experiment has found that low-height underfloor plenums (7 in. [0.18 m] and lower) can provide uniform airflow performance across a 3,200-ft^2 (300-m^2) area of a building.[14] The report recommends that, on average, at least 3 in. (75 mm) of clear space for airflow should be provided in addition to the height required for other factors (e.g., fan coil boxes, ductwork, etc.).

6. Problems with applicable standards and codes. Since UFAD technology is relatively new to the building industry, its characteristics may require consideration of unfamiliar code requirements and may be in conflict with the provisions of some existing standards and codes. Three ASHRAE standards have direct relevance to UFAD systems. ANSI/ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy,* specifies a “comfort zone,” representing the optimal range and combinations of thermal and personal factors for human occupancy. The current version of Standard 55 was revised to allow for higher air velocities than the previous version of the standard if the occupant has control over the local air speed, a characteristic of most UFAD systems.

ANSI/ASHRAE Standard 62-1999, *Ventilation for Acceptable Indoor Air Quality,* provides guidelines for the determination of ventilation rates that will maintain acceptable indoor air quality. The revised version of Standard 62 is expected to allow some adjustment in ventilation rates based on the ventilation effectiveness of the air-distribution system, a feature that may give credit to UFAD systems. However, the standard (and most building codes) also require that minimum ventilation rates be delivered whenever spaces are occupied. UFAD systems that allow individuals to reduce or even shut-off local supply diffusers must include a task/ambient control strategy to avoid the possible buildup of unperceived pollutants to unhealthy levels.

Task/ambient conditioning (TAC) systems are designed to maintain overall ventilation and comfort conditions throughout the ambient space, despite these kinds of actions at the local or task level. Increased hours of operation of the economizer will mitigate this effect to some degree. ANSI/ASHRAE Standard 113-1990, *Method of Testing for Room Air Diffusion*, is the only existing building standard for evaluating the air diffusion performance of an air-distribution system. Currently, only applicable to conventional overhead systems, Standard 113-1990 is now being revised to be compatible with UFAD, TAC, and displacement ventilation systems.

Local building and fire codes need to be considered early in the design process. Code officials having limited experience with UFAD systems have been known to create unexpected roadblocks due to misunderstandings or narrow interpretations of code language. In some jurisdictions, the unrestricted size of a large open underfloor air supply plenum and the combustibility of cabling and other materials contained in the plenum are restricted by fire codes. Revisions and exceptions that are more compatible with UFAD technology may be forthcoming as additional research results are obtained.

Conclusion

Rarely has an innovative HVAC system concept offered UFAD’s combined potential of cost and energy savings, and health, comfort and productivity benefits. The popularity of UFAD technology is now approaching that of VAV technology when it was first introduced. The availability of design guidelines and design tools, fundamental research on key technology issues, and whole-building performance data from completed projects will be critical to supporting the successful development of this important new direction in HVAC system practices and integrated building solutions. As the industry gains knowledge and experience to recognize the differences between UFAD and conventional overhead systems, it can be expected that UFAD technology will be here to stay.

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